# A Thermodynamic Approach to Steam-Power System Design

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Chemical industries in general consume great amounts of energy, and in the past several years it has become very important to make a strong effort to conserve energy in design and operation. Among the several kinds of problems faced in a steam-power system design, the problem of determining system structure and design conditions is most important. In solving the problem with directly acceptable results, it is desirable to build a sound basis for gaining deep insights into the energy conservation problem. The paper is concerned with a thermodynamic approach to steam-power system design. The practical usefulness of the present method is illustrated by solving a problem of steam-power system design in a petroleum refinery.

## Introduction

The energy situation throughout the world in recent years has necessitated a reevaluation of existing technologies and provided opportunities for design innovations. The need for energy conservation is serious, and various methods for efficient use of energy have been applied, especially in chemical industries that consume great amounts of energy.

A steam-power system for a chemical plant is one of several systems which should be examined carefully from the viewpoint of energy conservation, because the steam-power system not only supplies to the chemical plant great amounts of energies of different quality but also consumes large amounts of energy resources in itself.

In the previous work done by Nishio and Johnson (1977) and Nishio (1977), the problem of determining an economically optimal system structure and design conditions for the steam-power system was solved by use of a mathematical programming technique. Though the mathematical programming approach is quite useful, it is also desirable to build a sound basis for gaining deeper insights into the energy conservation problem. In this respect, thermodynamics is useful, since it produces more detailed technical information on energy conservation. This usefulness has been shown in several applications by Umeda et al. (1977, 1978) and Itoh et al. (1979).

In this paper, the problem of determining an energy conserving system structure and design conditions for the steam-power system is defined and analyzed using the available energy concept. A strategy for steam-power system design has been constructed on the basis of systematic use of heuristic rules derived to decrease the loss of available energy as much as possible. The usefulness of the present approach is illustrated by a practical example.

## Problem Statement

The steam-power system is a part of the total system representing an entire plant in Figure 1. Process systems and the steam-power system are major elements of the total system and are mutually dependent. The steam-power system must generate steam at certain pressure or temperature levels and electric power required mainly by the process systems. As compared with process systems, the steam-power system has a greater requirement for flexibility and reliability, as well as for good economic performance. This is due to the difference in its roles and the requirements imposed by the process systems. The total amounts of steam and power required for large and complex process systems are highly changeable depending on the various operation modes.

Thus it is necessary to design the steam-power system in such a way that the system satisfies several objectives simultaneously. It is possible in principle to deal with the design problem as a multi-objective optimization problem. The multi-objective optimization problem involves several mutually dependent problems such as those of maximizing flexibility and reliability, minimizing operating and investment costs, etc., and each design problem should be studied respectively in its specialized area. In the past, the steam-power system had fairly large allowance and redundancy so that its flexibility and reliability were increased to satisfy the requirements of the process systems. These criteria were accomplished at the expense of increasing costs.

Due to the change in the energy situation, a more energy-efficient system must be designed. In particular, it has become very important to decrease energy consumption. In the present study, the problem of steam-power system design is dealt with from the viewpoint of realizing the minimum amount of energy inputs subject to utilizing commercially available units.

In thermodynamic analysis, "energy" and "available energy" balances based on First and Second Laws are equally important. The available energy of a system is defined as the maximum useful (net) work which would be obtained by bringing the system (which is enclosed and allowed to communicate only with the surrounding atmosphere) to its dead state, that is, its equilibrium state with the temperature, pressure, and composition of the atmosphere. In the steady-state flow system, the available energy of a mixture, where such factors as kinetic and potential energies are practically negligible, is defined as

$$a = \int_{S'_0}^{S'} \mathrm{d}a = \int_{S'_0}^{S'} (\mathrm{d}h - T_0 \mathrm{d}s) = h - T_0 S - (h_0 - T_0 S_0) = h - T_0 S - \mu_0 \quad (1)$$

where $S'$ and $S'_0$ represent a state under consideration and the dead state, respectively.

For any system or its element, input streams can be converted into output streams depending on the design or operating conditions of the system or element. The conversion is governed by the following input-output equation (2) in general form, which includes a set of basic

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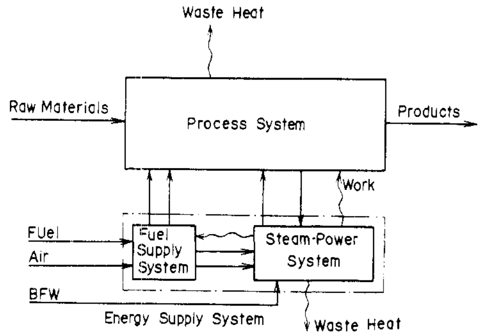


**Figure 1.** Total system.

material, energy, and available energy balance equations (3), (4), (5)

$$\boldsymbol{Z}_{ni} = \boldsymbol{F}_{ni}(\boldsymbol{X}_{n1}, \boldsymbol{X}_{n2}, ..., \boldsymbol{X}_{nJ}, \boldsymbol{D}_n) \quad (2)$$

$$\sum_j\sum_k x_{njk} - \sum_i\sum_l z_{nil} = 0 \quad (3)$$

$$\sum_j\sum_k x_{njk}h_{jk} - \sum_i\sum_l z_{nil}h_{il} - W_n - Q_n = 0 \quad (4)$$

$$\sum_j\sum_k x_{njk}a_{ik} - \sum_i\sum_l z_{nil}a_{il} - W_n - A_{nL} = 0 \quad (5)$$

where $\boldsymbol{X}_{nj}$ ($j$ = 1, 2, ..., $J$) and $\boldsymbol{Z}_{ni}$ ($i$ = 1, 2, ..., $I$) denote state vectors of input and output streams regarding the $n$th subsystem which include $x_{njk}$, $z_{nil}$, $x_{njk}h_{jk}$, etc. as their components. $\boldsymbol{D}_n$ are design or operating variables. In order to have meaningful solutions in practice, it is necessary to define feasible regions for design or operation of the subsystem as follows

$$\boldsymbol{G}_n(\boldsymbol{X}_{n1}, \boldsymbol{X}_{n2}, ..., \boldsymbol{X}_{nJ}, \boldsymbol{Z}_{n1}, \boldsymbol{Z}_{n2}, ..., \boldsymbol{Z}_{nI}, \boldsymbol{D}_n) \geq 0 \quad (6)$$

which includes

$$Q_n \geq 0 \quad (7)$$

$$A_{nL} \geq 0 \quad (8)$$

The relationship representing a system structure among any subsystems of which the total system consists can also be expressed in the following general form.

$$X_{nj} = \sum_m\sum_i \delta_{nj}^{mi} Z_{mi} \quad (9)$$

where $\delta_{nj}^{mi}$ is a structural variable, and it has one or zero values indicating that two subsystems are connected or not.

A general problem of energy conservation for a system design is to minimize the amount of energy input which corresponds to minimization of the loss of available energy, as is easily derived from eq 5, although the degree of achieving the goal depends on the activeness of constraints. The problem is defined as follows

$$\min_{\{\delta_{nj}^{mi}, D_n\}} x_E \quad (10)$$

subject to eq 2, a set of equality constraints including eq 3, 4, and 5, eq 6, a set of inequality constraints including (7) and (8), and eq 9, a set of structural relationships.

The problem of energy conservation for the steam-power system is defined in the same way. It can also be decomposed into the following three subproblems, as clarified in the latter section, for given quality and quantity of energy required.

(Subproblem 1). Determination of a basic system structure

$$\min_{\{\delta_1\}} x_E \quad (11)$$

subject to eq 2, 6, and 9, which involve equations for design or operation of boilers, turbines, etc.

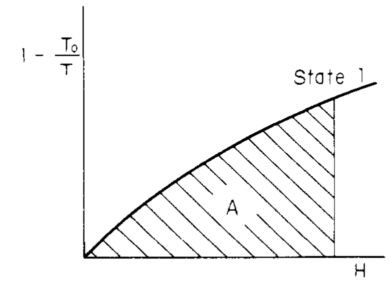


**Figure 2.** Available energy at state 1.

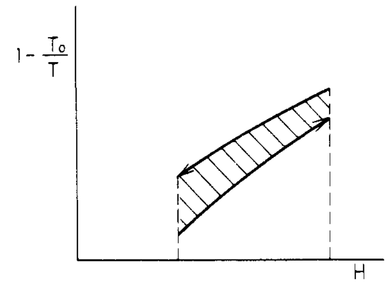


**Figure 3.** Available energy loss on heat transfer.

(Subproblem 2). Determination of design variables. For a given set of $\{\delta_1\}$

$$\min_{\{\boldsymbol{D}_n\}} x_E \quad (12)$$

subject to eq 2, 6, and 9.

(Subproblem 3). Determination of turbine allocation. For a given set of $\{\delta_1\}$ and $\{\boldsymbol{D}_n\}$

$$\min_{\{\delta_2\}} x_E \quad (13)$$

subject to

$$\boldsymbol{Z}_{ni} = \sum_j M_{nj}\boldsymbol{X}_{nj} \quad (14)$$

$$\boldsymbol{R}_n(\boldsymbol{X}_{n1}, \boldsymbol{X}_{n2}, ..., X_{nJ}, \boldsymbol{Z}_{n1}, \boldsymbol{Z}_{n2}, ..., Z_{nI}, \boldsymbol{D}_n) \geq 0 \quad (15)$$

and eq 9, where eq 14 is a linearized one derived by giving $\{\delta_1\}$ and $\{\boldsymbol{D}_n\}$ and eq 15 is a set of linearized inequality constraints.

## Steam-Power System Design Based on Available Energy Analysis

**System Analysis.** As described in the previous section, the present problem is to minimize the loss of available energy in the steam-power system. From eq 1, the available energy of a stream can be expressed as

$$a = \left(\int_{P_0}^{P} V\,\mathrm{d}p\right)_{T_0} + \left(\int_{T_0}^{T}\left(1 - \frac{T_0}{T}\right)C_\mathrm{p}\,\mathrm{d}T\right)_P - \mu_0 \quad (16)$$

The first, second, and third terms on the right-hand side are concerned with pressure, temperature, and composition of the stream, respectively.

The degree of improvement for energy utilization in the steam-power system is analyzed by using a heat-availability diagram which can show an available energy change of the stream with respect to its temperature change. In the case of an isobaric change for a given composition, the first and second terms of eq 16 remain constants. Since the isobaric heat capacity, $C_\mathrm{p}$, is equal to $(\partial h/\partial T)_p$, the third term is represented, as shown in Figure 2, by the area enclosed by Carnot efficiency, $1 - (T_0/T)$, and heat flowrate, $H$, which is the product of specific enthalpy and mass flowrate. In

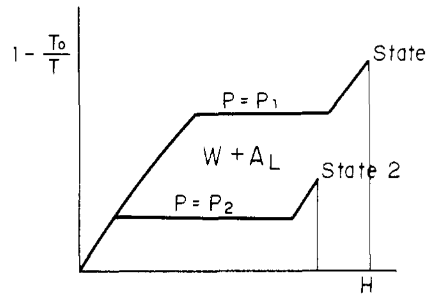


**Figure 4.** Available energy balance on pressure change.

a heat transfer process, the loss of available energy is expressed in terms of difference of available energy change between heat donor and heat receiver as seen in Figure 3. It follows from Figure 3 that the less the temperature difference between two streams, the less the loss of available energy becomes.

For the adiabatic pressure change from state 1 ($T_1$, $P_1$) to state 2 ($T_2$, $P_2$), provided that $P_1$ is greater then $P_2$, the available energy balance between these states is expressed as

$$\left(\int_{P_0}^{P_1} V\, \mathrm{d}p\right)_{T_0} + \left(\int_{T_0}^{T_1}\left(1 - \frac{T_0}{T}\right)C_p\, \mathrm{d}T\right)_{P_1} = \left(\int_{P_0}^{P_2} V\, \mathrm{d}p\right)_{T_0} + \left(\int_{T_0}^{T_2}\left(1 - \frac{T_0}{T}\right)C_p\, \mathrm{d}T\right)_{P_2} + W + a_L \quad (17)$$

where $a_L$ denotes the loss of available energy associated with the change of state. The first terms of both sides of eq 17 are concerned with the pressure change of liquid stream which corresponds to boiler-feed-water in the present study, and the difference between these terms is negligibly small. Therefore, the change of available energy can be presented on the heat availability diagram as given in Figure 4, in which the difference of values on the abscissa between states 1 and 2 indicates the enthalpy difference that corresponds to the shaft work of turbines. Keenan's "effectiveness" (work/available energy change) of a turbine (Keenan, 1932) can be easily obtained from the diagram. The difference between the actual work output and available energy change corresponds to the loss of available energy.

Similarly, the change of available energy in fuel combustion can be presented on the heat availability diagram. Since fuel combustion usually takes place at nearly atmospheric pressure, the effect of pressure change on available energy can be neglected. A large part of chemical available energy of the fuel is transformed into thermal and chemical available energy in the combustion reaction, and the chemical available energy of the combustion gas is unusable in practice. As shown in Figure 5, the thermal available energy of the combustion gas can be given on the diagram in the same manner as in Figure 2. $T_F$ corresponds to theoretical flame temperature and the difference in enthalpies at $T_F$ and $T_0$ corresponds to the low heating value of fuel used. If the excess air ratio decreases, the theoretical flame temperature becomes higher and thermal available energy discharged also increases. However, the combustion at theoretical ratio of air to fuel required by the stoichiometric relationship does not give maximum output of available energy, but it is possible to have a larger amount of available energy by preheating air and/or fuel. For simplicity of graphical presentation, it is assumed that heat capacity of the mixture of fuel and air is equal to that of combustion gas, and that temperature of preheater is

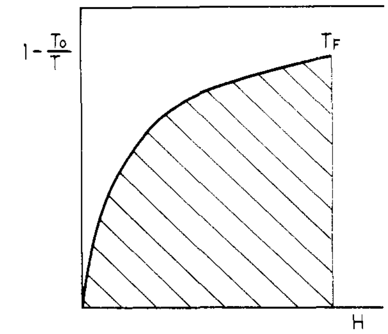


**Figure 5.** Available energy on fuel combustion.

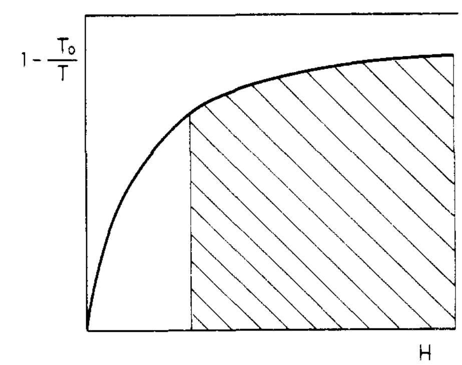


**Figure 6.** Influence of air preheater to available energy.

allowed to have an infinitesimal approach temperature. These assumptions lead to representation of the available energy by the area with slanting bars in Figure 6. If the combustion reaction could be carried out at thermodynamic equilibrium by increasing the preheating and controlling the heat discharged, it would give the maximum thermal available energy output. This is not possible in any industrial boiler, and loss of available energy is inevitable to some extent.

In addition to these losses of available energy, there exists heat loss through the boiler wall and that associated with flue gas at rather high temperature. Including these heat losses, the overall balance of available energy in a typical steam-power system may be represented as in Figure 7. The axis of the abscissa shows that the energy balance holds. The area below each line implies the available energies to be discharged by respective energy carriers. Except for the powering section, available energy losses are shown by areas between two composite lines which can be drawn by collecting the stream segments at the same temperature level. Examination of Figure 7 shows that the minimization of the amount of energy input to the system is equivalent to that of loss of available energy.

## Method of System Design

Thermodynamic analysis of available energy has played a central role in deriving a set of heuristic rules useful to the determination of system structure $\{\delta_1\}$ and design variables $\{D_n\}$. Based on the analysis described in the previous section, some instructions for the system design can be proposed as summarized in Table I. A strategy for steam-power system design has been developed on the basis of utilizing the instructions in Table I. For solving a problem of optimal driver allocation, the linear programming technique is used according to the reasons described below.

Major facilities for power generation usually consist of generator-drive turbines as utility facilities and a number of mechanical-drive turbines with medium and small ca-

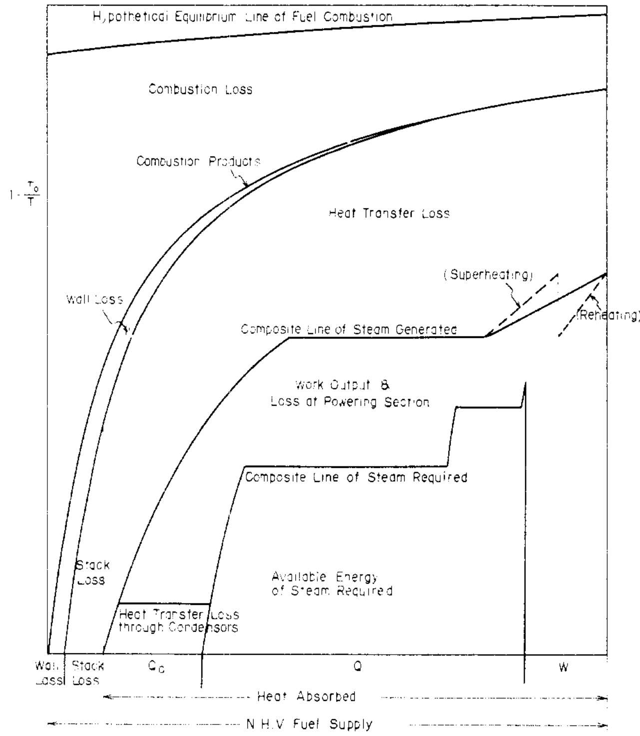


**Figure 7.** Overall balance of available energy in a typical steam-power system.

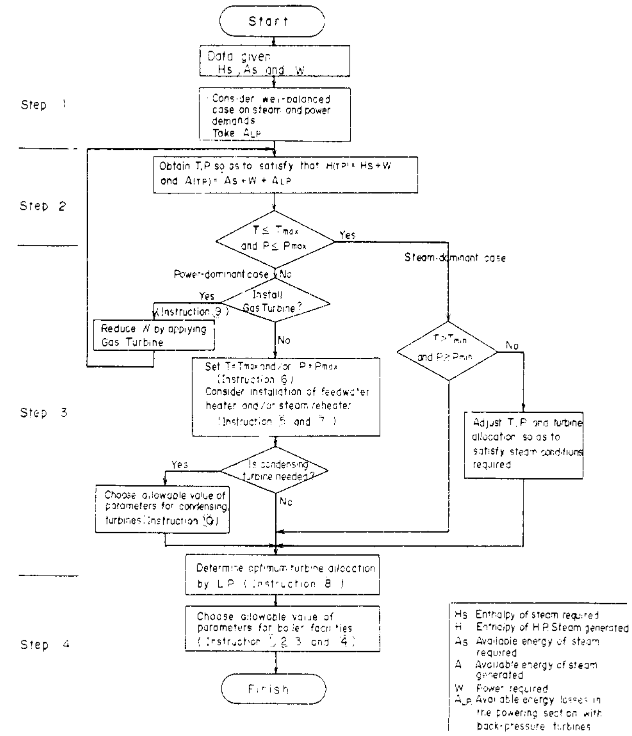


**Figure 8.** Strategy for steam-power system design.

**Table I. Instructions for Steam-Power System Design Based on Available Energy Analysis**

| available energy analysis | design instructions |
|---|---|
| reduce the loss in the combustion zone | 1. installation of air heater;[a]<br>2. to lower the excess air ratio;[a]<br>9. installation of gas turbine |
| reduce the loss through the wall of boiler facilities | 3. to strengthen the insulation of the furnace wall |
| reduce the loss to flue gas | 1. installation of air heater;<br>2. to lower the excess air ratio;<br>4. to lower the flue gas temperature |
| reduce the loss in the heat transfer section of boiler facilities[b] | 5. installation of feedwater heater;<br>6. to raise the boiler pressure and temperature;<br>7. installation of reheater |
| reduce the loss at the powering section[b] | 8. employment of turbines with high efficiency;<br>10. to reduce condenser duty for condensing turbines |

[a] The loss reduced moves into the heat transfer section of boiler facilities. [b] Effective in a power-dominant case.

pacities for process uses such as pumps and compressors located within the battery limit of the process system. There exist two kinds of loss available energy accompanied by a state change of steam: one is due to a change of steam pressure and the other is due to mixing of steams of different temperatures under constant pressure. The latter case can usually be neglected. The most important task in the powering section is how to utilize efficiently a change of available energy on a change of steam pressure. Reducing available energy losses is achieved by employing minutely designed turbines under appropriate conditions. In practice, however, turbines are selected not only from standardized units commercially available but also from a number of combinations of driver allocation for a given number of power demands and steam conditions at different pressure and temperature levels. Since this problem of optimal driver allocation has been formulated as subproblem 3 in the preceding section, it can be solved by the linear programming technique.

Eventually the procedure of steam-power system design is established as shown in Figure 8. The strategy of steam-power system design is characterized by two cases, i.e., steam-dominant and power-dominant cases. The case called power-dominant requires employing both back-pressure and condensing turbines to satisfy power demands, whereas the case called steam-dominant requires using only back-pressure turbines to satisfy power demands.

In step 1, basic data of steam and power demands are prepared and also an overall loss of available energy in the powering section using back-pressure turbines is estimated, with the object of realizing a well-balanced system which supplies steam and power demands without condensing turbines.

Step 2 determines whether the case under consideration is steam-dominant or power-dominant. Boiler pressure and temperature satisfying overall energy and available energy balances are obtained first, and if they exceed either allowable maximum pressure ($P_{max}$) or temperature ($T_{max}$), the case is regarded as power-dominant. If both of them are within the limits, the case is regarded as steam-dominant.

In step 3, if the case is power-dominant, design measures should be taken so as to reduce the loss of available energy as much as possible. As shown in Figure 8, installations of a gas turbine, steam reheater, or feedwater heater are some of these measures. However, which one should be chosen in practice depends first upon an overall evaluation of multi-objectives including economics, operability, and reliability. There is no priority on choice of the devices from the viewpoint of energy conservation alone.

In the case where condensing turbines must be employed, upper limit values for vacuum and moisture of

Table II. Steam and Power Demands

| item | demand |
|---|---|
| electricity | 32 030 kW |
| M.P. steam (16 kg/cm² g, 260 °C) | 125.1 ton/h |
| L.P. steam (3.5 kg/cm² g, 148 °C) | 187.3 ton/h |
| deaerated water | 257 ton/h |
| external power | |
| no. 1 | 818 kW |
| no. 2 | 1965 kW |
| no. 3 | 2020 kW |
| no. 4 | 1530 kW |
| no. 5 | 1940 kW |
| no. 6 | 3120 kW |
| no. 7 | 85 kW |
| no. 8 | 440 kW |
| no. 9 | 203 kW |
| no. 10 | 650 kW |
| internal power | |
| no. 11 (BFW pump) | to be calculated |
| no. 12 (boiler draft fan) | to be calculated |
| no. 13 (cooling water pump) | to be calculated |
| cooling water | 7306 ton/h |
| condensate import | 120.1 ton/h |
| steam import | |
| 1. M. P. steam | 224.0 ton/h |
| 2. L. P. steam | 50.2 ton/h |

exhaust steam should be used to specify design conditions for condensing turbines.

If the case is steam-dominant, the boiler has a potentiality in producing steam having more available energy than required for power generation. However, there is a danger of incurring a greater loss of available energy than expected by allowing a disordered combination of driver allocation, after steam conditions at the boiler are set on the basis of energy and available energy balances. Therefore, it is necessary to obtain an optimal combination of driver allocation for this case as well as for the power-dominant case.

The problem of driver allocation can be formulated as that of obtaining an optimal steam-power distribution network which leads to minimizing the loss of available energy of steam generated. It can be solved by the linear programming technique as already described.

In step 4, boundary values of parameters for boiler facilities allowable for reducing the loss of available energy are employed, aiming to raise the boiler efficiency.

## Illustrative Example

To illustrate the application of the method described in the previous section, the problem of a steam-power system design in a petroleum refinery of 200 000 BPSD capacity is taken as an example. Table II shows the design requirement which gives the steam and power demands for the refinery. It is assumed that maximum boiler pressure and temperature are preset as 100 kg/cm² and 448 °C.

It is first necessary to clarify whether the present case is steam-dominant or power-dominant. Figure 8 gives that the present case is identified as power-dominant. Although there is no priority on a choice of the devices from the viewpoint of energy conservation as noted before, only a feedwater heater is installed without steam reheater and gas turbine, and an optimal combination of driver allocation is obtained next. As described before, the problem of optimum driver allocation can be formulated as the linear programming problem. Figure 9 and Table III show the block-flow diagram of the steam-power system and the information necessary to formulate the problem. Figure 10 presents a result by solving the problem using an IBM code MPSX (Mathematical Programming System Extended). By comparing the result given in Figure 10 with Table IV which shows efficiency of each turbine when it is allocated at the respective sections for each power demand, the interpretation of the result regarding the driver allocation can be summarized as follows.

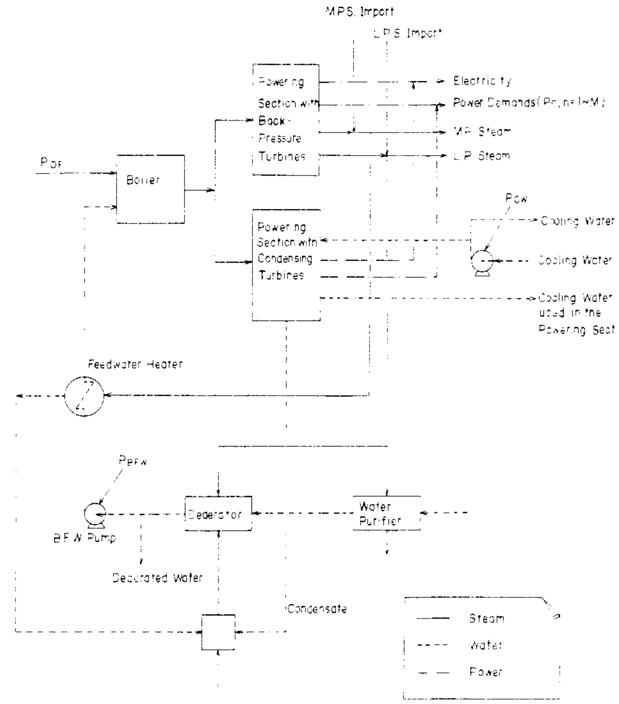


Figure 9. Back-flow diagram of the steam-power system.

Table III. Equipment/Facility Conditions

| equipment/facility | conditions |
|---|---|
| water purifier | steam consumption 8% of water to be treated |
| deaerator | pressure 0 kg/cm² g, temperature 100 °C |
| feedwater heater | heat donor (M.P. steam), 260 °C; 203 °C<br>heat receiver (BFW), 100 °C; 200 °C |
| boiler | blow-down rate, 5%<br>power required for boiler draft fan, 3.64 kW/ton of steam generated<br>boiler efficiency, 90%<br>low heating value, 10 500 kcal/kg |
| generator-drive turbine with condenser | exhaust steam pressure, 120 mmHg; moisture, 10.5%<br>temperature of condensate, 55 °C<br>outlet temperature of 50 °C cooling water<br>overall efficiency, 72% |
| pump for B.F.W. | inlet pressure, 0 kg/cm² g,<br>outlet pressure, 104 kg/cm² g<br>inlet temperature, 100 °C<br>pump efficiency, 65% |
| pump for cooling water | inlet pressure, 0 kg/cm² g,<br>outlet pressure, 7 kg/cm² g<br>inlet temperature, 30 °C<br>pump efficiency, 65% |

"Drivers should be allocated successively for the larger power demand so that their respective effectiveness may become as high as possible." Though this statement may be used as one of heuristic rules on the driver allocation, detailed studies would be necessary to justify it.

As the result of choosing allowable values of parameters for boiler facilities so as to raise boiler efficiency as high

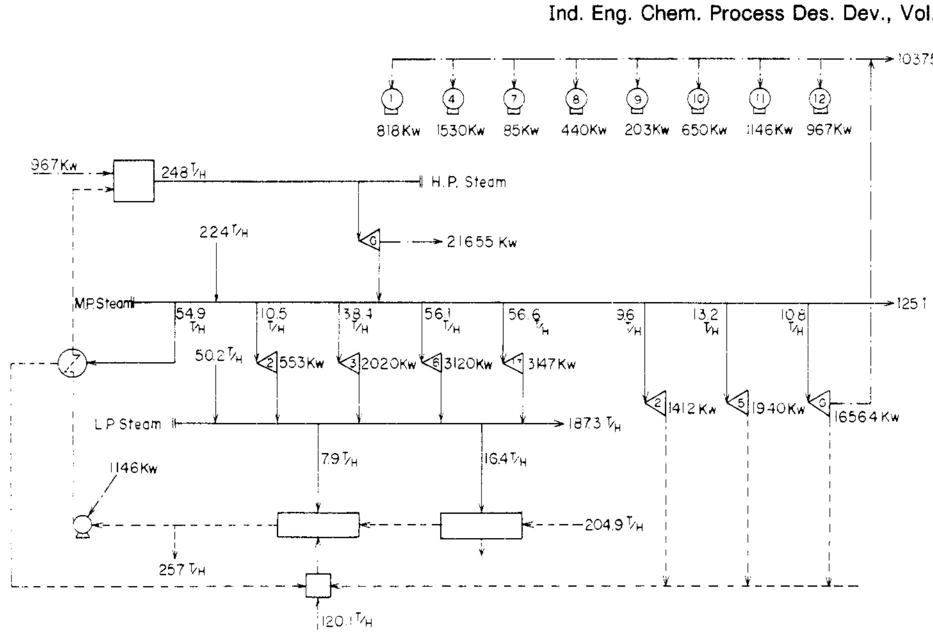


**Figure 10.** Steam and power balances including optimum driver allocation.

Table IV. Turbine Efficiency at Each Power Demand

| power demand no. | power, kW | turbine efficiency H.P. M.P. | H.P. M.P. | H.P. condensate | M.P. L.P. | M.P. condensate | motor efficiency | (generator turbine) × (motor) efficiency |
|---|---|---|---|---|---|---|---|---|
| 1 | 818 | 0.5 | 0.5 | 0.53 | 0.64 | 0.63 | 0.94 | 0.677 |
| 2 | 1965 | 0.6 | 0.6 | 0.62 | 0.71 | 0.69 | 0.95 | 0.684 |
| 3 | 2020 | 0.6 | 0.6 | 0.62 | 0.71 | 0.69 | 0.95 | 0.684 |
| 4 | 1530 | 0.59 | 0.59 | 0.61 | 0.7 | 0.68 | 0.95 | 0.684 |
| 5 | 1940 | 0.6 | 0.6 | 0.62 | 0.71 | 0.69 | 0.95 | 0.684 |
| 6 | 3120 | 0.66 | 0.66 | 0.65 | 0.75 | 0.71 | 0.95 | 0.684 |
| 7 | 85 | 0.42 | 0.42 | 0.44 | 0.5 | 0.48 | 0.91 | 0.655 |
| 8 | 440 | 0.44 | 0.44 | 0.46 | 0.59 | 0.57 | 0.935 | 0.673 |
| 9 | 203 | 0.42 | 0.42 | 0.44 | 0.5 | 0.48 | 0.93 | 0.670 |
| 10 | 650 | 0.5 | 0.5 | 0.52 | 0.63 | 0.62 | 0.94 | 0.677 |
| 11 | 1146 | 0.53 | 0.53 | 0.54 | 0.67 | 0.66 | 0.95 | 0.684 |
| 12 | 967 | 0.5 | 0.5 | 0.53 | 0.64 | 0.63 | 0.94 | 0.677 |
| 13 | 3147 | 0.66 | 0.66 | 0.65 | 0.75 | 0.71 | 0.96 | 0.691 |

as possible, the amount of fuel consumption is determined as 168 MMkcal/h.

## Discussion

Although the present study is confined to the problem of energy conservation for the steam-power system design under constant steam and power demands required, these demands are actually adjusted adequately in pursuing energy conservation for the process system so as to minimize the loss of available energy in the total system. Inadequate employment of steam-header conditions as well as process-steam conditions might result in a great amount of available energy loss. Practical treatment of such energy conservation for the total system is made using the two-level approach. Coordination between the process system and the steam-power system is quite important from the overall viewpoint of energy conservation. Steam and power demands in the process system should be treated as variables and it is necessary to solve iteratively the problems of steam-power system design as well as the process system design until the coordination is completed. The strategy shown in Figure 8 allows use of the linear programming technique at step 4 and it may be preferable to replace the use of the technique by certain heuristics. It is, however, tedious to allocate each driver manually by constructing steam and power balances using heuristics. Therefore, it is considered practical to determine an optimal combination of driver allocation by the linear programming technique.

## Conclusion

The typical steam-power system has been analyzed from the viewpoint of energy conservation using the heat availability diagram derived by the available energy concept in thermodynamics. A method of steam-power system design has been proposed using design instructions derived from the results of available energy analysis. The usefulness of the proposed approach has been illustrated by a practical example.


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## Nomenclature

$A$ = available energy of a stream or available energy of steam generated, kcal/h
$A_{nL}$ = available energy loss in $n$th subsystem, kcal/h
$a$ = specific available energy or a stream, kcal/kg
$C_p$ = isobaric heat capacity, kcal/kg K
$\boldsymbol{D}_n$ = decision vector of $n$th subsystem
$\boldsymbol{F}$ = state equation vector representing the relation between input and output streams
$\boldsymbol{G}$ = constraint vector
$H$ = heat flowrate of a stream or heat flowrate of steam generated, kcal/h
$h$ = specific enthalpy of a stream, kcal/kg

$M_{nj}$ = transformation matrix from $j$th input to $i$th output stream of $n$th subsystem
$p$ = pressure of a stream, kg/cm$^2$
$Q_n$ = waste heat in $n$th subsystem, kcal/h
$R_n$ = linear inequality constraints of $n$th subsystem
$S$ = entropy of a stream, kcal/kg K
$S'$, $S'_0$ = a state and the dead state of a stream
$T$ = absolute temperature of a stream, K
$T_0$ = environment temperature, K
$V$ = volume of a stream, m$^3$
$W$ = work generated at $n$th subsystem, kcal/h
$X_{nj}$ = $j$th input stream vector of $n$th subsystem
$X_{nj}$ = flowrate of $j$th input stream of $n$th subsystem, ton/h or kcal/h
$x_{njk}$ = $k$th component of $j$th input stream of $n$th subsystem, ton/h
$x_E$ = amount of energy input, ton/h
$Z_{ni}$ = $i$th output stream vector of $n$th subsystem
$\delta_{nj}^{mi}$ = structure variable implying that a flow enters from $i$th stream of $m$th subsystem into $j$th stream of $n$th subsystem
$\delta_1$ = basic system structure of steam-power system
$\delta_2$ = structure variable indicating turbine allocation
$\mu$ = chemical potential of a stream, kcal/kg

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# Wood Gasification in a Fluidized Bed

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Gasification of oak sawdust in the Synthesis Gas From Manure (SGFM) pilot plant at Texas Tech University has been evaluated. The SGFM reactor operates as a countercurrent fluidized bed in which a biomass feedstock is fed to the top of the reactor and is fluidized by an air-steam mixture fed to the bottom of the reactor. Using oak sawdust from Missouri as the feedstock, the gas yields were 1.1 to 1.4 L/g daf feed when the average reactor temperature was 600 to 800 °C. The gas contained about 4% $C_2H_4$ and 11% $CH_4$. The gross heating value of the gas exceeded 11.2 MJ/m$^3$ in all cases. The gasification of wood is compared to previous results obtained for cattle manure. The differences are due to the relative amounts of cellulose, hemicellulose, and lignin in the feedstock.

## Introduction

Wood is one of the oldest energy sources known to man. It has been used for thousands of years to provide heat and light. When liquid and gaseous fossil fuels were discovered, the use of wood diminished because of the inconvenience associated with collecting, distributing, and using wood.

Due to the decreasing supply and increasing costs of fossil fuels, wood and other biomass feedstocks are once again being utilized as an energy source. For example, the forest products industry obtains nearly half its energy from wood residues (Tillman, 1978). Most of this is from spent liquor in the pulp and paper industry. Del Gobbo (1978) reported that forestry residues represent 4.2 Quads of available energy at present.

One method to minimize the inconvenience associated with wood is to convert it to a combustible gas by pyrolysis. Glesinger (1949) reports that wood pyrolysis was first performed in 1792 by Robert Mudoch. Since then wood has been used to produce a variety of fuels and chemicals. Recent interest in wood conversion processes has been increasing due to the desire to develop renewable energy resources and reduce the dependence on imported fossil fuels.

The Synthesis Gas From Manure (SGFM) process was developed at Texas Tech University in response to a local problem on the High Plains of Texas. Large amounts of cattle manure from feedlots present a serious disposal problem. The SGFM process was designed to produce ammonia synthesis gas from manure. Ammonia was chosen as the desired product because it is in high demand as a fertilizer in the agricultural region where the feedlots are located. It was also found that significant quantities of ethylene were produced in the SGFM process.

The SGFM process has been described by Halligan and Sweazy (1972), Halligan et al. (1975), and Beck et al. (1979). The heart of the process is a countercurrent, fluidized bed reactor. The biomass feedstock is fed to the top of the reactor and falls countercurrently to the steam and product gas in the reactor. This provides some flash drying of the cold feedstock in direct contact with hot product gas. Air and steam are introduced at the bottom of the reactor to partially combust the solids and fluidize the bed.

The advantage of this system is that fresh feed enters the pyrolysis zone of the reactor and does not encounter an oxidizing atmosphere. This results in the formation of significant amounts of olefinic hydrocarbons. These quickly exit the reactor and are quenched before they can decompose to lower molecular weight compounds. As a result, the gas produced in this process has a higher heating

 